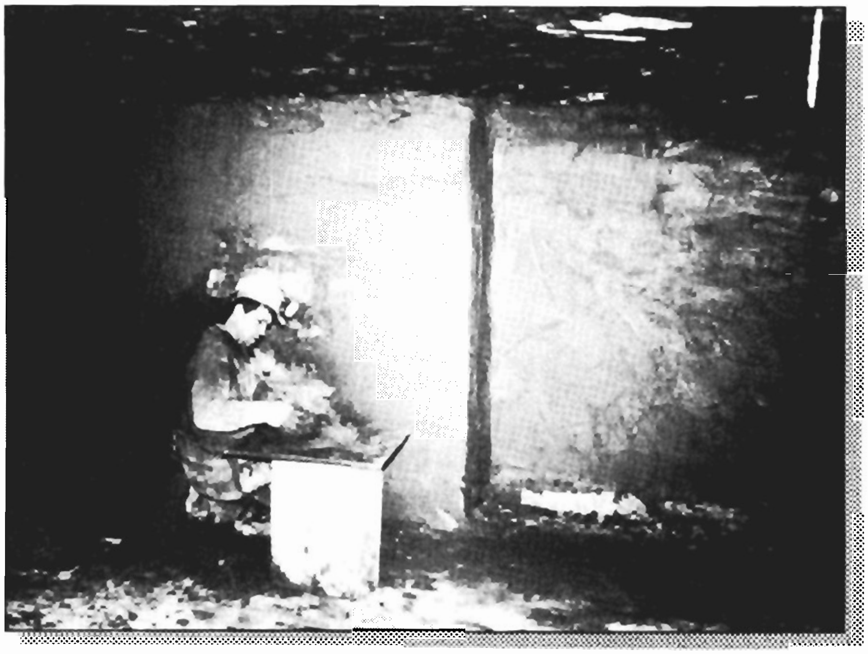
RI 9634

REPORT OF INVESTIGATIONS/1996

Evaluation of Polymer Construction Material and Water Trap Designs for Underground Coal Mine Seals

By Eric S. Weiss, William A. Slivensky, Mark J. Schultz, Clete R. Stephan, and Kenneth W. Jackson



UNITED STATES DEPARTMENT OF ENERGY

PITTSBURGH RESEARCH CENTER

Cover photo: Application of a cementitious surface coating to the face of a low-density cementitious block seal design within the Lake Lynn Experimental Mine. This seal design was evaluated, against a full-scale mine explosion, for its strength and air leakage characteristics. (Cover and inside photos by William A. Slivensky, Pittsburgh Research Center.)

Report of Investigations 9634

Evaluation of Polymer Construction Material and Water Trap Designs for Underground Coal Mine Seals

By Eric S. Weiss, William A. Slivensky, Mark J. Schultz,
Clete R. Stephan, and Kenneth W. Jackson

UNITED STATES DEPARTMENT OF ENERGY

PITTSBURGH RESEARCH CENTER

International Standard Serial Number
ISSN 1066-5552

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

h	hour	pct	percent
min	minute	s	second

Factors for Conversion to U.S. Customary Units

To convert from—		To—	Multiply by—
cm	centimeter	inch	0.3937
cm^2	square centimeter	square inch	0.155
kg	kilogram	pound	2.2046
kg/m^3	kilogram per cubic meter	pound per cubic foot	0.0625
km	kilometer	mile	0.6214
kPa	kilopascal	pound (force) per square inch, gauge	0.145
kPa	kilopascal	inch of water (pressure)	4
L	liter	gallon	0.2642
m	meter	foot	3.2808
m^2	square meter	square foot	10.764
m^3	cubic meter	cubic foot	35.3147
m^3/s	cubic meter per second	cubic foot per minute	0.5886
mg/L	milligram per liter	ounce per cubic foot	0.001
t	metric ton	short ton	1.1023
°C	degree Celsius	degree Fahrenheit	1.8 and add 32

Visit our Mining Health and Safety Research site on the Internet, accessible via http://www.usbm.gov.

EVALUATION OF POLYMER CONSTRUCTION MATERIAL AND WATER TRAP DESIGNS FOR UNDERGROUND COAL MINE SEALS

By Eric S. Weiss,[1] William A. Slivensky,[2] Mark J. Schultz,[3] Clete R. Stephan,[4] and Kenneth W. Jackson[5]

ABSTRACT

The Pittsburgh Research Center (PRC)[6] and the Mine Safety and Health Administration (MSHA) are participating in a research program to evaluate the strength characteristics and air leakage resistance of seals and water trap designs for use in underground coal mines. This program is being conducted at PRC's Lake Lynn Laboratory near Fairchance, Fayette County, PA.

Seals designed with a 40-cm-thick polymer (polyurethane) and aggregate core between two dry-stacked (no mortar) concrete block walls (coated on outby sides) withstood a 138-kPa pressure pulse while maintaining acceptable air leakage rates. Similar seal designs utilizing a 97-cm-thick, 91-kg/m^3-density, polymer-only core did not survive; however, a 51-cm-thick, 203-kg/m^3-density, polymer-only core seal successfully withstood the explosion pressures.

Evaluations of cellular concrete seal designs have shown that a two-pour slurry injection technique did not adversely affect the strength of the 1.2-m-thick seals when subjected to a 138-kPa pressure pulse. Two seal designs utilizing low-density cementitious block have also been evaluated with successful results.

In addition to seal strength tests, various 15- and 30-cm-diam U-shaped water trap pipes and a water trough design were evaluated under explosion conditions and were shown to be inadequate when evaluated under worst-case conditions. Simple modifications to the various water trap designs were successful in preventing the passage of explosion flame through the trap.

[1]Mining engineer, Pittsburgh Research Center, U.S. Department of Energy, Pittsburgh, PA.
[2]Physical science technician, Pittsburgh Research Center, U.S. Department of Energy, Pittsburgh, PA.
[3]Mining engineer, Ventilation Div., Mine Safety and Health Administration, Pittsburgh, PA.
[4]Principal mining engineer, Ventilation Div., Mine Safety and Health Administration, Pittsburgh, PA.
[5]Electronics technician, Pittsburgh Research Center, U.S. Department of Energy, Pittsburgh, PA.
[6]This work originated under the U.S. Bureau of Mines prior to transferring to the U.S. Department of Energy on April 4, 1996.

INTRODUCTION

During the normal course of underground coal mining, it sometimes becomes necessary to install seals to isolate abandoned or worked-out areas of a mine. This practice eliminates the need to ventilate those areas. Seals may also be used to isolate fire zones or areas susceptible to spontaneous combustion. To effectively isolate areas within a mine, a seal should—

- Minimize leakage between the sealed area and the active mine workings so as to prevent toxic and/or flammable gases from entering the active workings;
- Be capable of preventing an explosion initiated on one side from propagating to the other side; and
- Continue its intended function for 1 h when subjected to fire conditions.

Title 30, Part 75.335 of the Code of Federal Regulations (CFR) (*1*)[7] requires a seal to "withstand a static horizontal pressure of 20 pounds per square inch [138 kPa]."

PRC and MSHA are jointly investigating the capability of various seal construction materials and designs to meet or exceed the requirements of the CFR. This work is in support of PRC's Disaster Prevention research program to improve safety for underground mine workers. Previous research (*2*) indicates that it would be unlikely for overpressures exceeding 138 kPa to occur very far from the explosion origin provided that the area on either side of the seal contained sufficient incombustible and minimal coal dust accumulations. This is the first full-scale test program to evaluate seal designs in entry geometries similar to those of current U.S. underground coal mines. Previous evaluation of seal designs were conducted in the smaller entries of PRC's Experimental Mine at Bruceton, PA (*2*). The 2.7-m-wide by 1.8-m-high entries of the Bruceton Experimental Mine were typical geometries for U.S. mines in the early 1900's when the Experimental Mine was first developed. However, technological advances in ventilation, roof support, and mining machinery have resulted in increased entry sizes.

PRC's seal research program had previously addressed, through explosion testing at the Lake Lynn Experimental Mine (LLEM), the integrity of solid-concrete-block seals (*3*), low-density cementitious block seals (*4*), cementitious foam seals (*3*, *5*), and wood block seals (*6*). Various other alternative seal designs have more recently been constructed and tested under this seal research program. This effort included several series of seal designs utilizing polymer, cellular concrete, and low-density cementitious block construction materials.

A growing concern within the mining industry and MSHA centered on the design and effectiveness of water trap devices. 30 CFR 75.335(c) states that "(1) a corrosion-resistant water pipe or pipes shall be installed in seals at the low points of the area being sealed and at all other locations necessary when water accumulation within the sealed area is possible; and (2) each water pipe shall have a water trap installed on the outby side of the seal." (*1*) These U-shaped traps are designed to allow the passage of water through an explosion-resistant seal so as to prevent the buildup of a large impoundment of water against the seal. The trap design must be able to prevent the passage of mine gases through the trap.

The research program focused on whether typical water trap designs could successfully prevent the passage of an explosion flame through the trap, even during periods when there may be minimal liquid in the trap. The primary concern, therefore, was whether a 138-kPa explosion pressure pulse could forcibly remove the water from the trap, thus enabling the explosion flame to propagate through the trap and ignite a flammable methane (CH_4) atmosphere on the active side of the seal. Various types and sizes of water traps were installed and evaluated under full-scale conditions within the LLEM.

The overall objective of this research is to determine whether seals constructed from various materials and designs can withstand a 138-kPa CH_4-air explosion without losing their structural integrity. The seal must not only be physically strong, but also minimize leakages. A safety and cost benefit will also result from these evaluations in that many of these new seal designs require less material and worker-hours to install than the standard solid-concrete-block seal.

Full-scale research into the development of explosion- and leakage-resistant seals assists MSHA in setting adequate standards and provides useful information to the industry for the improvement of mining safety. As new seal construction materials and designs become available, performance data from full-scale explosion tests are needed to evaluate their strength characteristics. Additionally, air leakage determinations are essential for all seal types. The LLEM can be used to provide these data. MSHA has requested technical assistance in this area.

This report discusses the construction techniques, testing methods, and test data collected for these most recent series of explosion-resistant seal and water trap designs for underground coal mines.

[7]Italic numbers in parentheses refer to items in the list of references at the end of this report.

EXPERIMENTAL PROCEDURE

MINE EXPLOSION TESTS

All of the explosion and air leakage determination tests on the various seal designs were conducted in the LLEM (*7-8*). Lake Lynn Laboratory is one of the world's foremost facilities for conducting large-scale mining health and safety research. The LLEM is unique in that it can simulate current U.S. coal mine geometries for a variety of mining scenarios, including multiple-entry room-and-pillar mining and longwall mining.

Figure 1 shows a plan view of the LLEM. The underground entries consist of approximately 7,620 m of workings developed in the mid-1960's for the commercial extraction of limestone and 2,286 m of entries developed in 1980-81. These more recent entries are depicted in figure 1 as drifts A, B, C, and D, each of which is 520 m long and closed at the inby end, and drift E which is 152 m long and connects C and D drifts. The dimensions of the drifts and crosscuts are typical of modern U.S. geometries for coal mine entries and range from 5.5 to 6.0 m wide and approximately 2 m high.

Figure 2 shows an expanded view of the seal test area. CH_4 was injected into the closed end of C drift. A plastic diaphragm was used to contain the 10 pct CH_4-air mixture within the first 14.3 m of the entry (an approximate 190-m^3 zone). Electric matches, located at the closed end of the entry, were used to ignite the flammable CH_4-air mixture. Before the ignition of the CH_4, a 60-t, track-mounted, concrete and steel bulkhead was positioned across E drift to contain the explosion pressures in C drift. Barrels filled with water were located in the gas zone to act as turbulence generators to achieve the 138-kPa pressure pulse.

All of the seals were constructed in the crosscuts between the B and C drifts; these crosscuts are approximately 2 m high by 5.8 m wide. The average cross-sectional area of the crosscuts is 11.6 m^2.

INSTRUMENTATION

Each drift has 10 environmentally controlled data-gathering stations that house the instruments (shown in figures 1 and 2). Each data-gathering station houses a pressure transducer to measure the static pressure generated by the explosion and an optical sensor to detect the flame travel. A variety of other

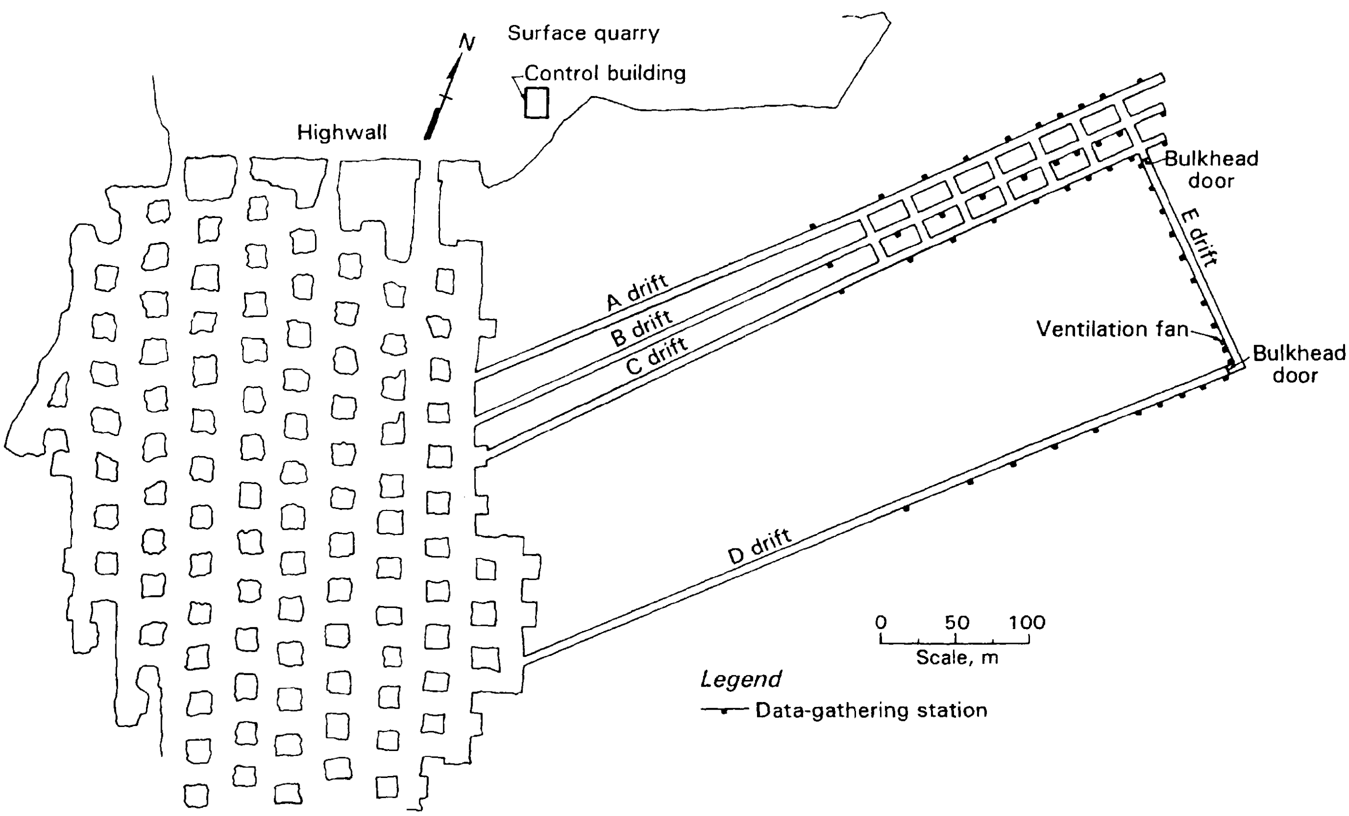


Figure 1.—Plan of the Lake Lynn Experimental Mine.

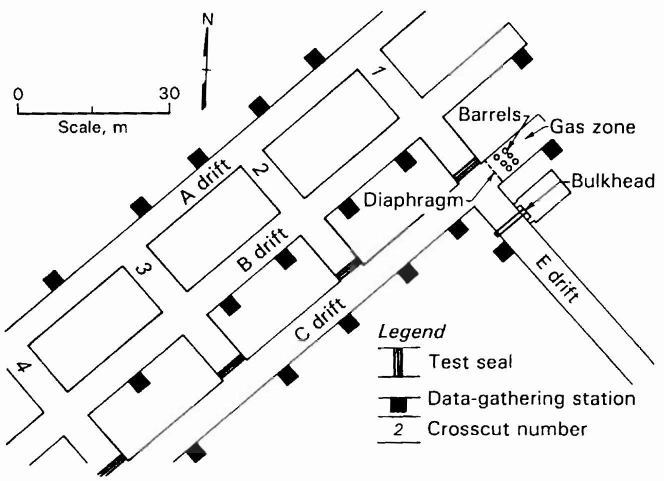


Figure 2.—Diagram of seal test area in the Lake Lynn Experimental Mine.

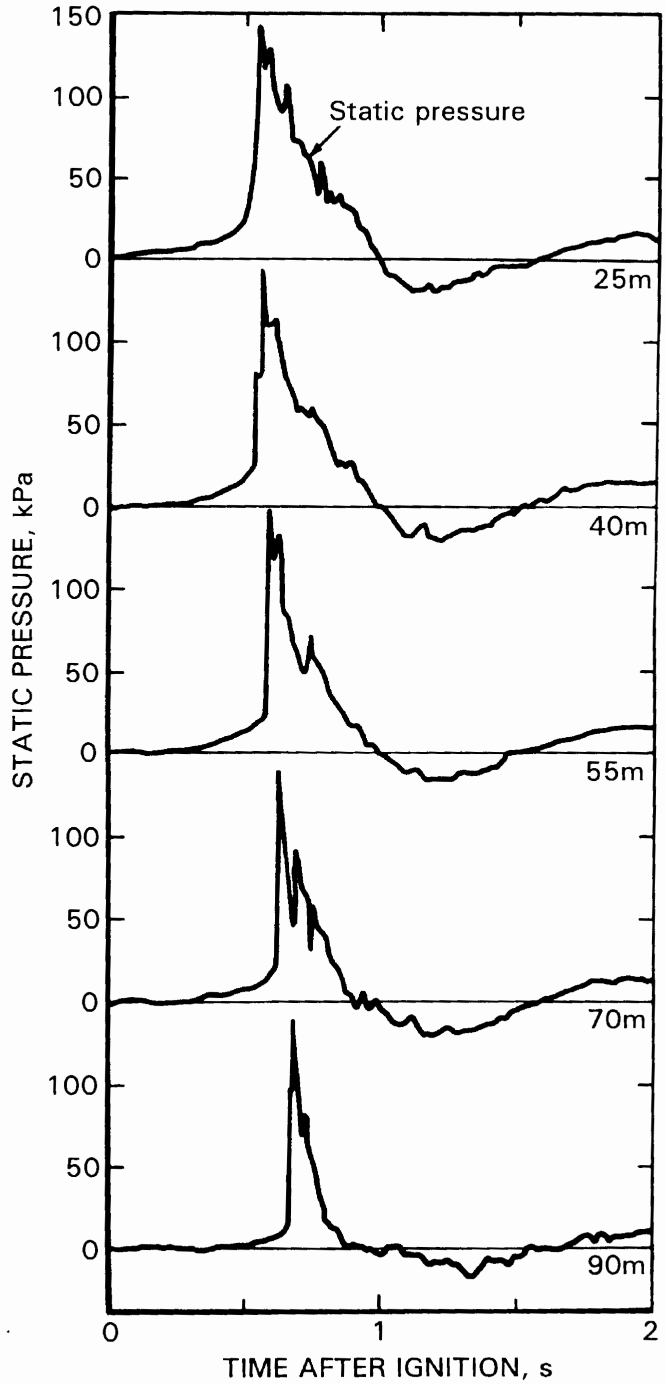


Figure 3.—Typical computer-generated static pressure transducer traces in C drift following a 138-kPa level explosion pressure pulse.

instruments, including high-speed cameras, have been interfaced to the data-gathering stations to provide a more detailed account of the explosion and subsequent effects on the seal and/or trap designs.

Figure 3 shows typical pressure traces from the static pressure transducers located in C drift just outby crosscut No. 1 (top trace) to just outby crosscut No. 3 (bottom trace). The pressure pulse generated by the ignition of the CH_4-air zone generally resulted in static pressure pulses ranging from 152 kPa at crosscut No. 1 to about 138 kPa at the most outby seal (in some instances as far outby as crosscut No. 5, or 150 m from the ignition source). Previous explosion studies conducted at the LLEM showed that the explosion pressure pulse decayed less rapidly with distance in the larger, more typically sized LLEM entries than in smaller entries presumably because of the smaller surface-to-volume ratio (*9*). The pressure pulses exerted on each seal were measured by interpolation of the data from the nearest C drift pressure transducers both inby and outby the crosscut position. An additional pressure transducer was installed on the C drift (explosion side) face of the seal in crosscut No. 1. The pressure data recorded from this transducer correlated well (less than 7-kPa difference) with the pressure data obtained through interpolation.

An important measure of the damaging potential of the explosion pressure pulse is the pressure impulse, which is the time integral of the pressure profile or the area under the pressure-time curve. The destructive forces of the explosion blast wave depend on both the maximum peak overpressure and the impulse (*9*). Under current evaluation criteria, a seal design need only withstand a minimum static pressure pulse of 138 kPa while maintaining its air leakage resistance; impulse requirements have yet to be defined. For this reason, seal designs were frequently subjected to higher level explosion pulses in the LLEM as a means to evaluate the various seal designs against higher impulse loadings.

AIR LEAKAGE DETERMINATIONS

An important factor to be considered for any seal design is its air impermeability, or its ability to minimize leakage from one side of the seal to the other. Measurements of the air leakages across the seals were conducted before and after each of the explosion tests. For these air leakage tests, the D-drift bulkhead door (see figure 1) was closed. This directed all of the ventilation flow (from E drift) to the seal locations in C drift. A double brattice cloth or curtain was erected across C drift outby the last seal position (figure 4). This curtain effectively blocked the ventilation flow, which resulted in a pressurized area on the C-drift side of the seals. By increasing the speed of the four-level LLEM main ventilation fan while in the blowing mode, the resultant pressure exerted on the seals increased from approximately 0.25 kPa for the lowest fan speed setting to slightly over 1.1 kPa for the highest fan speed setting.

On the B-drift side of each of the seals, a diaphragm of brattice cloth was installed across the crosscut (figure 4) with a 465-cm^2 opening near the center. A vane anemometer was used to monitor the airflow through this opening.

During the construction of the seals, a copper tube was positioned through each of the seals, with one end of the tube extending out on each side. This tube served to measure the air pressure exerted by the fan on each seal. During these leakage determination tests, a pressure gauge was attached to the copper tube on the B-drift side to monitor the differential water pressure across the seal.

As the ventilation fan speed was increased, the pressures and the air flows through each seal were recorded. Based on data (*3-4*) previously collected during the testing program with solid-concrete-block and cementitious foam seals, guidelines for acceptable air leakage rates through seals were developed for this program. The air leakage rates through the seals during both preexplosion and postexplosion leakage tests were evaluated against these established guidelines. Table 1 shows these maximum acceptable air leakage rates in cubic meters per second as a function of pressure differential in kilopascals. For pressure differentials up to 0.25 kPa, air leakage through the seal must not exceed 0.05 m^3/s; for pressure differentials over 0.75 kPa, air leakage must not exceed 0.12 m^3/s. The differential pressure was measured using the copper tubing through the seal. The flow rate was calculated from the linear air speed measured by the vane anemometer and the area of the opening through the brattice cloth behind each seal.

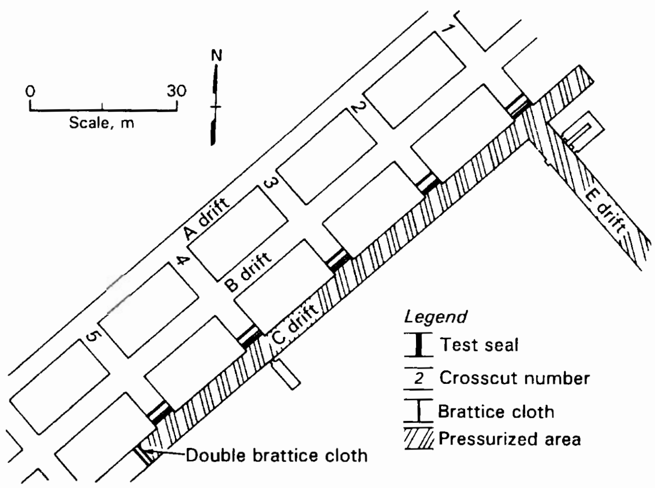


Figure 4.—Pressurized entry for leakage determination rates across the seals.

Table 1.—Guidelines for air leakage through a seal

Pressure differential, kPa	Air leakage, m^3/s
Up to 0.25	<0.05
Up to 0.50	$\leq$0.07
Up to 0.75	$\leq$0.10
More than 0.75	$\leq$0.12

A seal that did not withstand the 138-kPa pressure pulse (i.e., a postexplosion visual inspection of that seal revealed substantial structural damage) was considered not to meet the minimum standards as specified in the CFR for an underground coal mine seal and therefore failed. Postexplosion air leakage tests were not performed on seals that exhibited significant damage in terms of large cracks and/or block displacement. Seals that withstood the pressure pulse with little or no outward signs of damage were tested for air leakage resistance.

TEST RESULTS

POLYMER FOAM SEALS

Numerous seal designs utilizing a polymer (polyurethane foam) material as part of the seal construction process were tested in the LLEM. This polymer seal design concept was developed and patented by MICON, Glassport, PA. The polymer grout is comprised of two chemical components: polyisocyanate and polyol resin. Each of these components was contained in separate 208-L drums. The liquid components were injected at a 1:1 ratio using a two-component polymer pump and blended together with an in-line static mixer at the injection end of the hose. When using the polymer components (as when using any material), all safety precautions on the proper storage, transportation, and handling must be followed, including wearing of appropriate personal protective equipment as specified in the materials safety data sheets.

Test Series 1

The first series of seals, installed in March 1993, was a composite structural design consisting of two dry-stacked (no mortar) hollow-core, concrete block walls with a polymer and limestone aggregate (No. 57 stone; stone size ranged from 1.0- to 1.9-cm core) (figure 5). Seal locations in crosscut Nos. 2, 4, and 5 were thoroughly cleaned by the MICON personnel before seal installation. (In addition to the polymer and aggregate core seal designs in crosscut Nos. 2, 4, and 5, two other seal designs of different construction material were installed in crosscut Nos. 1 and 3.) The concrete block walls of the MICON seals were built with staggered joints, but were not required to be hitched or trenched into the ribs or floor. The aggregate was placed between the block walls in 10- to 15-cm layers. The polymer (320-kg/m^3-design density) was then pumped separately onto each aggregate layer, thereby consolidating the aggregate layer and concrete block walls and providing adhesion to the mine surfaces (figure 6). Within a few minutes after mixing, the polymer would begin to expand. This expansion raised and integrated the aggregate with the polymer. This process was repeated until the entire void space between the two concrete block walls was filled to the mine roof (figure 7). After the installation of the top concrete block course, additional polymer was injected into the core to ensure a complete expansion of the polymer to the mine roof (figure 8). The small voids between the top course and the mine roof were then filled with 1-cm-thick patio stone and wooden wedges (figure 8). The exposed block on each exterior wall was then coated with a sealant from MSHA's list of approved mine sealants for coal mine use (in this instance, DuPont's trowelable mine sealant (#90YTF2H)).

The three seals of the first test series had a design core thickness between the block walls of 76 cm for seal 1, 46 cm for seal 2, and 31 cm for seal 3. The expansion of the polymer caused a horizontal movement of the dry-stacked front wall blocks for two of the smaller core seals, resulting in an increased core thickness that ranged from 46 to 51 cm for seal 2 in crosscut No. 4 and 31 to 41 cm for seal 3 installed in crosscut No. 5. This movement of the front concrete block wall was primarily caused by the construction technique employed. During the installation of the seals in this first test series, each

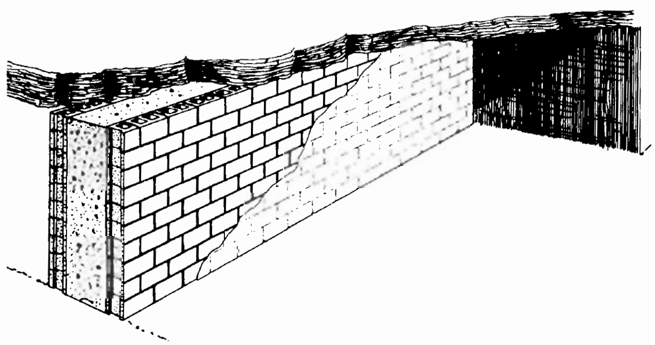


Figure 5.—Conceptual drawing of the composite polymer seal design.

Figure 6.—Injection of the polymer to the dry aggregate layer between the block walls.

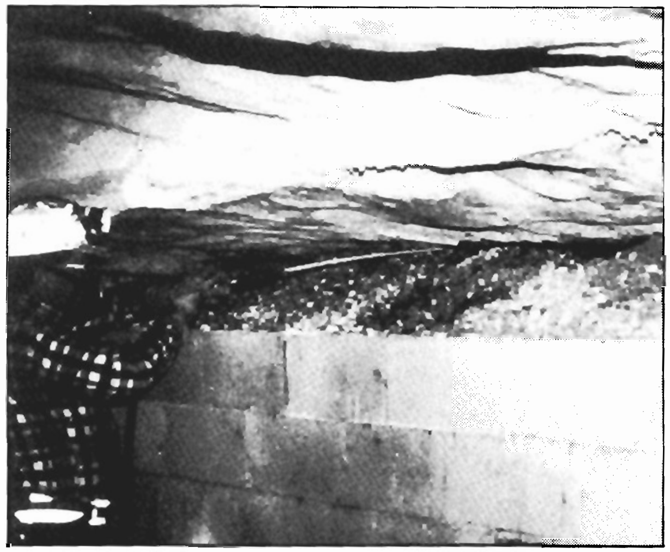


Figure 7.—Completion of the polymer and aggregate core near the mine roof.

Figure 8.—Final injection of the polymer between the concrete block walls to ensure closure to the mine roof.

layer of new aggregate was stowed in place as soon as the polymer was applied to the previous aggregate layer without waiting for the lower lift to fully expand. This caused some horizontal movement of the expanding polymer instead of the desired vertical rise, resulting in an outward bulge of the partially constructed front concrete block wall. This movement of the front block wall did not adversely affect the strength of these seals because additional aggregate and polymer were required to be used within the expanded seal core volume, thus providing additional mass to the final seal design. However, during subsequent test series with the polymer seals in the LLEM, hydraulic props were utilized to anchor large surface area support devices (such as wood pallets) against the partially constructed front seal wall to prevent any horizontal movement of that wall due to the expansion of the polymer (see figure 8). In addition, each of the polymer-saturated aggregate lifts was given sufficient time (generally 10-15 min) to fully expand before the next lift was initiated.

During actual coal mine installations, multiple seals are constructed simultaneously. Following the injection of the polymer onto the dry aggregate layer at one seal location, the polymer would then be applied to the dry aggregate layers on numerous adjacent seals. Therefore, before work would resume on the first seal, sufficient time would elapse to allow the polymer-saturated aggregate layer from that first seal to fully expand before the addition of the next aggregate layer.

Before subjecting the seals of the first test series to the explosion overpressures, air leakage tests were conducted on these seals. As listed in table 2, the leakage rates across the polymer and aggregate core seal designs 1, 2, and 3 were within the air leakage guidelines established for this program as listed in table 1. The seals were then subjected to a pressure pulse that was generated from the ignition of a CH_4-air zone at the closed end of the mine entry.

Postexplosion observations showed that the seals survived the 145-kPa pressure pulse with no outward signs of damage (see table 3, seals 1-3). Postexplosion air leakage tests showed that each of these polymer and aggregate core seal designs maintained acceptable leakage resistance (see table 2, seals 1-3).

A second explosion test (test 2 in table 3 for seals 1-3) was conducted to evaluate the strength characteristics of these same three polymer and aggregate core seal designs when subjected to a higher level pressure pulse. The same polymer seals had already withstood the 145-kPa pressure pulse (more than the required minimum of 138 kPa) while maintaining acceptable air leakage resistances. The stronger pressure pulse was achieved by using a zone of pulverized coal dust in addition to the CH_4 zone. The coal dust was loaded on shelves suspended from the mine roof. The shelves were positioned every 3 m starting just inby the 14.3-m-long gas zone and extended 78 m along the entry. When suspended in the mine atmosphere, the coal dust reached a concentration of 100 mg/L; this assumed a complete and uniform distribution of the coal dust throughout the entry before the flame arrival. The pressure and flame from the ignition of the CH_4 zone dispersed and ignited the coal dust, which resulted in the development of a pressure pulse that ranged from 221 kPa at seal 1 to 276 kPa at seal 3. This stronger pressure pulse completely destroyed seals 1 and 3.

The 46-cm-thick polymer and aggregate core seal (seal 2), as shown in figure 9, withstood the higher pressure pulse (269 kPa). Very little damage occurred to this seal, except for the displacement of the front face of many of the hollow-core concrete blocks on both sides of the seal. However, the inside block faces of these hollow-core blocks were still intact and maintained the isolation of the polymer and aggregate core from the mine environment. The sealant around the perimeter of the seal was also intact. Postexplosion leakage determinations on this surviving seal 2 in crosscut No. 4 could not be conducted because the seals in crosscut Nos. 1-3 were destroyed.

Table 2.—Summary of seal air leakage rates as a function of pressure differential (air leakage rates, m^3/s)

Seal type	Seal No.	Preexplosion pressure differential		Postexplosion pressure differential		Outcome
		0.25 kPa	1.1 kPa	0.25 kPa	1.1 kPa	
Polymer/stone	1	0.02	0.06	0.03	0.06	Pass.
	2	.03	.09	.04	.12	Pass.
	3	.03	.08	.04	.10	Pass.
Polymer only	4	.05	.13	.12	.25	Fail.
	5	0	<.01	NAp	NAp	Fail.
	6	.11	.25	NAp	NAp	Fail.
	7	.01	.03	NAp	NAp	Fail.
Polymer/stone	8	0	0	0	[1]0	Pass.
	9	0	0	0	[1].02	Pass.
	10	0	0	0	[1].03	Pass.
Polymer only	11	0	0	0	[1].02	Pass.
Cellular concrete	1	0	.02	0	.02	Pass.
	2	0	.05	.02	.07	Pass.
	3	0	.03	.01	.04	Pass.
	4	.03	.08	.04	.12	Pass.
Low-density block	1	0	.01	0	.01	Pass.
	2	0	.02	0	.02	Pass.

NAp Not applicable.
[1]0.96-kPa pressure differential.

Table 3.—Summary of test conditions and results for polymer seal designs

Test series No. and date	Seal No.	Crosscut No.	Block type	Overall seal thickness, cm	Designed core thickness, cm	Amount polymer, kg	Amount stonefill, kg	Average core density, kg/m^3	Explosion test outcome		
									Test 1	Test 2	Test 3
1 (Mar. 1993)	1	2	HC	117	76	1,045	—	—	145 kPa; passed.	221 kPa; failed.	NAp
	2	4	HC	86	[1]46	780	—	—	145 kPa; passed.	269 kPa; passed.	NAp
	3	5	HC	71	[2]31	680	—	—	145 kPa; passed.	276 kPa; failed.	NAp
2 (Oct. 1993)	4	1	HC	135	97	1,360	0	91	145 kPa; failed.	NAp	NAp
	5	2	LDF	137	[3]97	1,315	0	91	141 kPa; failed.	NAp	NAp
	6	3	None	97	97	1,315	0	91	138 kPa; failed.	NAp	NAp
	7	4	LDF	109	[4]69	1,000	0	91	131 kPa; failed.	NAp	NAp
3 (Mar. 1995)	8	2	S	71	41	838	2,585	734	136 kPa; passed.	124 kPa; passed.	193 kPa; passed.
	9	3	HC	71	41	825	2,336	641	134 kPa; passed.	117 kPa; passed.	200 kPa; failed.
	10	4	S	76	46	763	2,721	571	128 kPa; passed.	110 kPa; passed.	165 kPa; failed.
	11	5	S	91	51	1,385	0	203	117 kPa; passed.	103 kPa; passed.	159 kPa; passed.

NAp Not applicable.
HC Hollow-core concrete block. LDF Low-density foam block. S Solid-concrete block.
[1]Expansion of polymer caused block wall bowing to nearly 51 cm in center.
[2]Polymer expansion increased core thickness to 41 cm.
[3]Expansion of polymer increased core thickness to 112 cm in center section of seal.
[4]Expansion of polymer increased core thickness to 76 cm in center top sections of seal.

NOTE.—Dash indicates no data available.

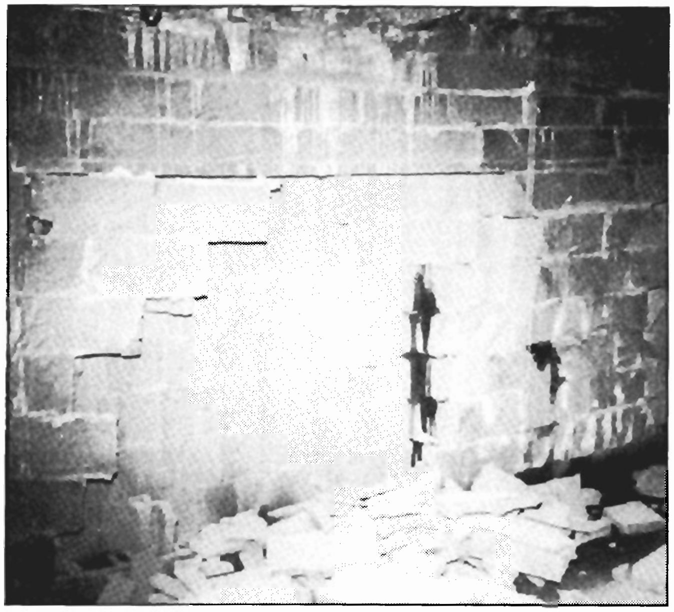


Figure 9.—Condition of the 46-cm-thick polymer and aggregate core seal design, which withstood a 269-kPa explosion pressure pulse.

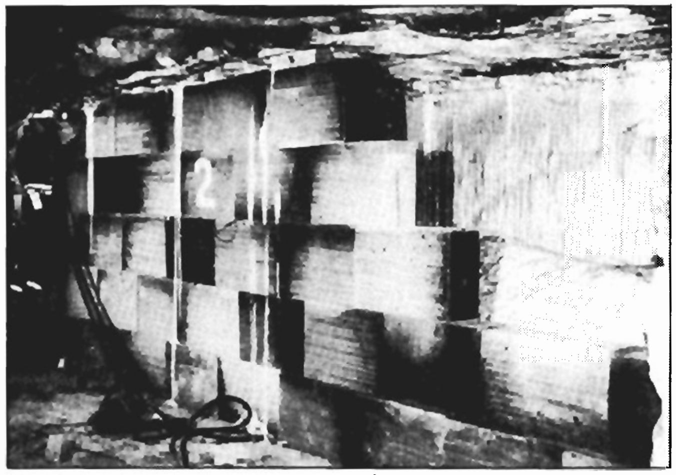


Figure 10.—Injection of the 91-kg/m^3-density polymer-only core.

Figure 11.—Condition of the 91-kg/m^3-density polymer-only core seal following the 141-kPa level explosion.

Test Series 2

During a second test series in October 1993, four additional polymer seal designs (table 3; seals 4, 5, 6, and 7) were tested in the multiple entries of the LLEM. Each seal was constructed with a polymer-only core (no aggregate). The design density of the polymer grout was 80 kg/m^3; based on core sampling, the actual density was approximately 91 kg/m^3. Three of the four seals utilized dry-stacked (no mortar) block walls (hollow-core concrete blocks for seal 4 in crosscut No. 1; low-density cementitious blocks for seal 5 located in crosscut No. 2) with a 97-cm-thick core of the polymer. The injection of the polymer between the two low-density cementitious block walls of seal 5 in crosscut No. 2 is shown in figure 10. Seal 6 in crosscut No. 3 consisted only of the 97-cm-thick polymer core; the block walls were removed after the polymer core was injected. This seal design was not intended for use in coal mines, but only as a means to evaluate the capability of the polymer itself to withstand the pressure pulse. Seal 7 in crosscut No. 4 consisted of the dry-stacked (no mortar) low-density cementitious blocks (average weight of 21 kg) with a 69-cm-thick core of the polymer. Upon completion of the injection of the polymer cores, the exterior wall faces of each of the seals were coated.

Following construction, these polymer-only core seals were air leakage tested, then subjected to the explosion pressure pulse. The air leakage rate measured across seals 5 and 7 fell well within the established guidelines (see table 2). However, seals 4 and 6 exceeded these air leakage guidelines at both the lower and higher pressure differentials. Postexplosion observations of the seals following the CH_4 ignition revealed that polymer-only core seals 5, 6, and 7 were completely destroyed by the pressure pulse, which ranged from 145 kPa at seal 4 in crosscut No. 1 to 131 kPa at seal 7 in crosscut No. 4 (table 3 and figure 11). Postexplosion air leakage rates, as measured at the surviving polymer-only core seal 4 in crosscut No. 1, were 0.12 m^3/s at a 0.25-kPa pressure differential, or over twice the required maximum leakage rate (see table 2, seal 4). The failure of the polymer-only core seal designs 5, 6, and 7 seemed to result from a combination of factors. It appeared that the polymer could not properly bond to the solid strata because of the presence of a very fine layer of dust particles that were present on the solid strata before the initial polymer injection. These dust particles bonded with much of the polymer and prevented direct polymer-to-strata contact, which, in turn, negatively impacted the adhesion characteristics of the polymer to the solid strata. The 91-kg/m^3-density polymer was also adversely affected by the surface moisture present on the solid strata, even though these surfaces appeared dry before the polymer injection. Observations of the postexplosion core showed that the surface moisture reacted with the liquid polymer during the initial injection period and significantly reduced the density of that initial polymer layer at the polymer and mine strata interface. Another contributing factor to these failures was the low overall mass (3,535 kg or less) of each of the polymer-only seal designs. The lower mass polymer-only seal designs failed. However, seal 4 in crosscut No. 1, which was constructed with the heavier hollow-core concrete blocks, apparently had sufficient mass (6,125 kg) to withstand the 145-kPa level pressure pulse, but was unable to maintain acceptable postexplosion air leakage rates. To date, the minimum mass of the various seal designs that survived the 138-kPa pressure pulse in the 11.6-m^2 crosscut of the LLEM is approximately—

- 12,000 kg for a standard concrete block seal (*3, 5*);
- 8,600 kg for a typical 1.2-m-thick cementitious foam seal (*3, 6*);
- 5,335 kg for the low-density cementitious block seals (*4, 6*); and
- 8,000 kg for the wood block seals (*6*).

To reduce the effects of excessive surface moisture and/or high relative humidity conditions, it was recommended that a higher density polymer (1,121 kg/m^3) be used to coat the mine surfaces and concrete block wall surfaces before the injection of the standard-density polymer. Surface moisture effects will be minimized by the use of this higher density polymer. The standard-density polymer used in the remainder of the core will readily bond to this cured higher density polymer on the mine strata and concrete block surfaces.

Test Series 3

In March 1995, a third series of polymer seal designs (table 3; seals 8, 9, 10, and 11) was tested in the LLEM to determine the minimum quantity of aggregate required. During the first test series (seals 1-3) with the polymer and aggregate core seals in March 1993, it had been very difficult to quantify the amounts of aggregate used because the material was delivered and handled in bulk form. For this third series, the aggregate was dried and packaged in plastic-wrapped 22-kg bags to eliminate the excessive surface moisture effects on the polymer expansion process, which was experienced when using bulk aggregate. This also allowed for increased accuracy in measuring the amount of aggregate used per lift and simplified the material handling effort by eliminating the need to hand shovel the aggregate into the core.

Two of the polymer and aggregate core seals evaluated during this third series were similar in design, except that the dry-stacked (no mortar) walls of seal 8 in crosscut No. 2 consisted of solid-concrete block (average 22 kg each) and seal 9 in crosscut No. 3 utilized hollow-core concrete block. Both designs maintained a nearly 41-cm-thick core of polymer (160-kg/m^3 design density) and aggregate. The core density was designed to be 560 kg/m^3, consisting of an aggregate density of 456 kg/m^3 and a final polymer density of 104 kg/m^3. Approximately 738 L, or 838 kg, of the liquid polymer was injected into the core volume, and 2,585 kg of aggregate was stowed between the walls of seal 8. The crosscut No. 2 dimensions for seal 8 were approximately 5.9 m wide by 2 m high, resulting in a core volume of 4.7 m^3. Based on the total amounts of polymer and aggregate used within the core, the final core density for seal 8 was calculated to be 733 kg/m^3. For seal 9 using the hollow-core concrete block walls, 730 L, or 825 kg, of liquid polymer and 2,336 kg of aggregate was used, resulting in a final core density of 640 kg/m^3 based on a core volume of nearly 5 m^3. Both seals required a total of nine lifts of the polymer and aggregate to complete the core. On average, 83 L of the liquid polymer and 250 to 320 kg of aggregate (11 to 14 bags) were used per lift. The total mass of seal 9 with the hollow-core concrete block was approximately 7,760 kg, compared with 10,120 kg for seal 8. The exterior wall faces of each seal were then coated.

Seal 10 in crosscut No. 4 was constructed in a manner similar to seal 8; however, this particular seal was designed to be more explosion-resistant. The two dry-stacked (no mortar) solid-concrete-block walls each included a modified 46- by 46-cm pilaster, which was located in the center of the wall (pilasters did not project into the void space between the two walls). The core thickness, or space between the two block walls, was 46 cm and required nine polymer and aggregate lifts to completely fill. A total of 763 kg of polymer and 2,721 kg of aggregate were required to complete the core, resulting in a final core density of 571 kg/m^3. The total mass for seal 10 was approximately 12,265 kg. The exterior wall faces were then coated.

Seal 11 in crosscut No. 5 consisted of a 51-cm-thick, polymer-only core between two solid-concrete-block walls. The solid-concrete blocks were dry-stacked (no mortar) with staggered vertical joints and installed with the 15-cm side of the block up. Approximately 480 blocks were used in this seal, which included a 41- by 41-cm center pilaster designed into each wall (similar to seal 10). Twenty-three lifts of a 160-kg/m^3-density polymer[8] was injected between the block walls into the 6.8-m^3 volume (6.1-m-wide by 2.2-m-high entry). A total of 1,225 L, or 1,385 kg, of polymer was required to complete the core, resulting in a final core density of 203 kg/m^3. The total mass for polymer-only core seal 11 was approximately 12,304 kg. The exterior wall faces were then coated.

During the preexplosion air leakage evaluations for this third test series, no leakage was detected through any of the seals against pressure differentials across each seal of up to 0.96 kPa (see table 2, seals 8-11). Following test 1 of the third test series, all four seal designs survived the pressure pulse (from 136 kPa at seal 8 in crosscut No. 2 to 117 kPa at seal 11 in crosscut No. 5) with no outward sign of damage (see table 3; seals 8-11). Postexplosion leakage rates (see table 2, seals 8-11) were also well within the accepted guidelines. The explosion pressure pulse for test 1 was lower than the required 138-kPa minimum

[8]This was the design density; actual density was approximately 203 kg/m^3 based on samples taken during the core injection.

pulse; therefore, additional tests were conducted against these seal designs. The pressure pulse generated during test 2 of this third series was also lower than anticipated, but each of the four seal designs survived this second explosion (table 3, seals 8-11). Test 3 resulted in pressure pulses ranging from 159 kPa at crosscut No. 5 (seal 11) to 200 kPa at crosscut No. 3 (seal 9). Even though these pressures were much higher than the required 138-kPa pressure pulse and this was the third consecutive explosion test conducted on these seals, the polymer and aggregate core seal 8 and the polymer-only core seal 11, both utilizing the solid-concrete-block walls, withstood these higher pressure pulses (table 3, seals 8 and 11). Following the evaluation of the polymer seals, seal 8, with the solid-concrete-block walls and 41-cm-thick polymer and aggregate core, was not removed from the mine and subsequently withstood a total of 14 consecutive mine explosions (pressure pulses ranging from 124 to 193 kPa).

To optimize seal performance, all construction techniques must be adhered to strictly. With the polymer seal designs, the mine surfaces must be free of all loose debris and dust accumulations. It is recommended that the mine surfaces be initially treated with a water-resistant polymer or a higher density polymer before the standard-density polymer materials are used. The polymer seal designs discussed in this report were installed under dry mine conditions within the LLEM; these polymer seal designs were not evaluated under wet mine conditions. Excess water at the seal site could adversely impact the polymer expansion process during the seal installation. For optimized performance, the polymer components should not be used at temperatures below 10 °C.

On average, a 10- to 15-cm-high aggregate layer saturated with the polymer typically experienced an additional vertical expansion of 13 to 20 cm within the relatively dry conditions (40-60 pct relative humidity) of the LLEM. Therefore, a fully expanded polymer and aggregate lift ranged from 23 to 35 cm high. During this polymer expansion process, a vertical movement of the aggregate also occurred and resulted in a distribution of the aggregate within the bottom 20 to 25 cm of the fully expanded lift. Generally, as was documented during the LLEM installation process, any increased height in the total lift beyond the first 20 to 25 cm consisted of polymer only (no aggregate). Subsequent observations of each of the core cross sections following removal of the seals from the mine verified these findings. Based on the outcome of these full-scale evaluations within the LLEM, the polymer composite seal designs, which have successfully met the requirements, have been approved for use in U.S. underground coal mines.

CELLULAR CONCRETE SEALS

Cellular concrete is a material similar to cementitious foam, which successfully withstood explosion pressures within the LLEM greater than 138 kPa (*3, 5*). Cellular concrete seal designs by R. G. Johnson and Co., Inc., Washington, PA, were evaluated primarily to determine if the slurry injection technique created a weakness in the seal. This technique involved a two-pour slurry injection process. There was concern that a potential plane of weakness may be created at the interface between the two cellular concrete pours that could adversely affect the strength of the seals. This concept is generally referred to as a cold joint.

Cellular concrete is an aerated cement with the foaming agent added during the slurry injection process. This differs from cementitious foams in that these foams are usually designed for their low densities and quick setting times with the foaming agents already included in the dry powder bags.

Four 1.2-m-thick seal designs utilizing a low-density, 1,380-kPa compressive strength cellular concrete were installed in the crosscuts between B and C drifts at the LLEM. Similar to the earlier cementitious foam seal designs constructed in the LLEM (*3, 5*), the wooden framework for each set of forms (spaced 1.2 m apart) consisted of upright posts wedged tightly to the mine roof and floor (figure 12). Interconnecting crossboards (2.5- by 15-cm rough-cut lumber) were then attached to these posts. The upright posts were on a maximum spacing of 76 cm; the crossboard spacings did not exceed 30 cm. A liner of brattice cloth covered the inside of each form wall and overlapped the inside mine surfaces approximately 10 cm. To minimize leakage of the slurry near the mine roof, thin L-shaped strips of steel were attached to the top of the posts to hold the brattice cloth overlap firmly to the roof. A 5-cm-diam injection port was installed through a center crossboard located near the roof. To ensure that the slurry completely filled to the mine roof, two similar-sized polyvinyl chloride (PVC) bleeder ports with

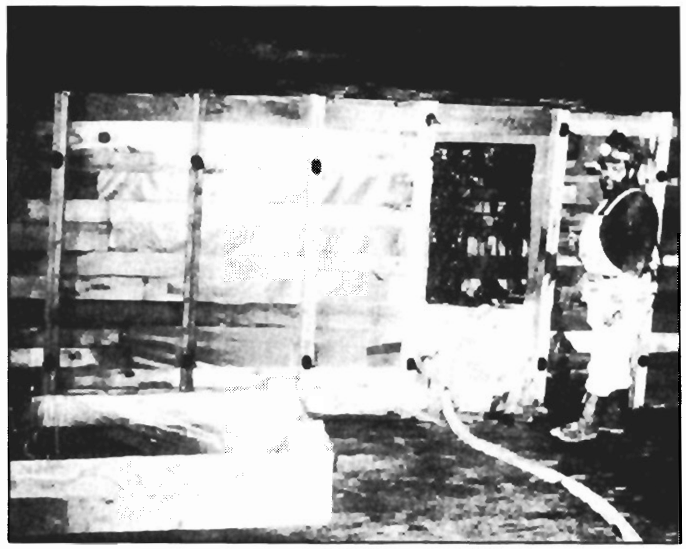


Figure 12.—Injection of the cellular concrete slurry between the wood and brattice cloth form walls.

valves were installed near the roof on both ends of the seal. Attached to each port was a pipe that extended halfway between the two form walls. At the end of each pipe was a 90° elbow, which was positioned within a few centimeters of the roof and rib line between the form walls. When the slurry began to flow through the bleeder ports, the valves on these ports were closed. This combination of a centrally located slurry injection port and a bleeder port at each end of the seal face provided a reliable method for ensuring that the slurry level was in direct contact with the mine roof following the second pour.

Approximately 14.5 to 15 bags of dry cement (about 315 kg) were used per cubic meter of injected slurry to provide a designed wet density of 608 kg/m^3 (560 kg/m^3 density when cured). Sampling from each seal during the slurry injection period confirmed both the density and compressive strength of the cellular concrete.

Each of the four seal forms was partially filled (two within 35 to 50 cm of the mine roof, two halfway to the 2-m-high roof) with the cellular concrete slurry and allowed to harden. After a minimum 18-h cure period, additional slurry was injected until closure to the mine roof was completed. A woven steel mesh was installed within two of the forms (one of which was to be filled halfway with slurry, the other to within 35 to 50 cm of the roof on the first pour) to provide reinforcement for increased flexural strength of the seals. These cellular concrete seals required approximately 20 worker-hours each to install (not including the time between the two pours), compared with a standard solid-concrete-block seal, which required about 72 worker-hours.

The four low-density, cellular concrete seals were allowed 30 days to cure (time period required for material to approach maximum strength characteristics), then subjected to air leakage and explosion testing. The preexplosion air leakage data for each seal were well within the established benchmark standards for these tests (see table 2). All four seal designs withstood the required explosion pressure pulse with no outward signs of damage (table 4). Postexplosion air leakage rates through the seals showed that the seals were within the acceptable levels (table 2). The two-pour cellular concrete injection technique apparently had no detrimental effect on the strength of the seals.

The seal designs were subsequently subjected to a second, stronger explosion test. The stronger pressure pulse was achieved by using a 65-m zone of pulverized coal dust in addition to the CH_4 zone. The pulverized coal dust was loaded on suspended shelves at a concentration of 150 mg/L, assuming uniform distribution of the coal dust within the entry during the explosion. The pressure and flame from the ignition of the CH_4 dispersed and ignited the coal dust zone, which resulted in the development of a 297- to 328-kPa pressure pulse through the seal zone. This stronger pressure pulse had no apparent outward effect on the cellular concrete seals 1 and 3, whose initial pour was close to the roof. Seals 2 and 4, which were only half-filled during the first pour, were completely destroyed by this higher pressure pulse (table 4).

Based on these full-scale LLEM evaluations, seals 1 and 3 designs, which had the initial pour of the cellular concrete slurry to within 50 cm of the 2-m-high mine roof, exhibited higher flexural strength than seals 2 and 4, which were only half-filled on the first pour. The effect of the woven steel mesh used in seals 1 and 2 was unclear until the two surviving seals (1 and 3) were being removed from the mine following the last explosion. After the removal of the wood and brattice cloth framework from the two surviving seals (both of these original seal forms were filled to within 50 cm of the mine roof on the first slurry pour), it was observed that seal 3 sustained numerous deep vertical fractures on both sides of the seal. Seal 1, which utilized the woven steel mesh within the seal body, revealed no such fracturing and only very minor surface cracking. It must be noted, however, that all four seal designs withstood the required minimum 138-kPa pressure pulse.

Table 4.—Summary of test conditions and results for the 1.2-m-thick cellular concrete seal designs

Crosscut and seal No.	Average height of first pour, m	Reinforcement	Average compressive strength, kPa	Explosion test outcome	
				Test 1	Test 2
1	1.7	Yes	1,675	145 kPa; passed.	327 kPa; passed.
2	1.0	Yes	1,390	148 kPa; passed.	297 kPa; failed.
3	1.6	No	1,870	138 kPa; passed.	310 kPa; marginal.[1]
4	1.0	No	2,075	124 kPa; passed.	328 kPa; failed.

[1] Seal withstood the explosion pressure pulse, but sustained numerous vertical fractures on both sides of the seal.

LOW-DENSITY CEMENTITIOUS BLOCK SEALS

A second series of full-scale seal designs utilizing the low-density cementitious block was conducted. The first test series was conducted in 1990 and resulted in the approval of three low-density cementitious block seal designs (*4, 6*). This second test series evaluated an alternative mortar and sealant, which is compatible with the low-density cementitious block. In addition, the methodology of construction was evaluated to provide for an improved seal design that required less block, thereby decreasing material handling and the risk of worker injury.

The Omega 384 block, manufactured by Burrell Mining Products International, Inc., New Kensington, PA, is a lightweight, glass-fiber-reinforced, cementitious block that is impervious to moisture and air leakage to pressure differentials up to 2 kPa. The blocks are 41 by 61 by 20 cm and weigh 19 to 20 kg each. A fiberglass-reinforced cement, Rite-Wall (manufactured by Scio Packaging, Scio, OH), was used for both the mortar at the block joints and the surface coating sealant on these two seal designs. A full 0.6-cm-thick joint of mortar was used for all block (similar surface coat thickness used as full-face coating on both sides of seal 1 and only on the inby side of seal 2). The seals were allowed a 30-day cure period.

These seals were designed to be keyed or trenched into the mine ribs and floor. This keying was simulated (to protect the long-term integrity of the LLEM ribs and floor) by bolting 15- by 15- by 1.3-cm-thick steel angle to the floor and ribs on both sides of the seal using 2.5-cm-diam case-hardened steel bolts (embedded a minimum of 30 cm) on 45-cm spacings. These bolts were grouted into the floor and ribs. In operating mines, keying of the seal is achieved by hitching or trenching to a depth of at least 10 cm into the solid strata of the ribs and floor before erecting the seal. The simulated keying, as used in the LLEM, has been permitted in place of the standard keying techniques and is used in some coal mines with hard, sandstone bottoms.

The design for both low-density block seals was essentially the same except for the size of the center-support pilaster. Each seal wall was 61 cm thick with a center interlocking pilaster. A 1.2- by 1.2-m pilaster was incorporated into the seal 1 design; seal 2 was constructed with a 1.8-m-wide by 1.4-m-thick pilaster (figure 13). The blocks were laid in a staggered pattern for both the main seal wall and the pilaster. All block surfaces were wet with water and brushed before installation to ensure good bonding with the mortar. Any void space between the block course and the ribs was filled with mortar. Wood planks (2.5 by 30 cm) were used across the top of the seal to span the gap between the last block course and the mine roof. The layer of planking above the low-density block was set in a thin layer of mortar. All of the planks were installed with staggered joints between the front and back planks. Wood wedges were used to tighten down the planks and fill any small void spaces. All planking and wedging to the main seal wall were conducted first, then the pilasters were planked and wedged in a similar manner.

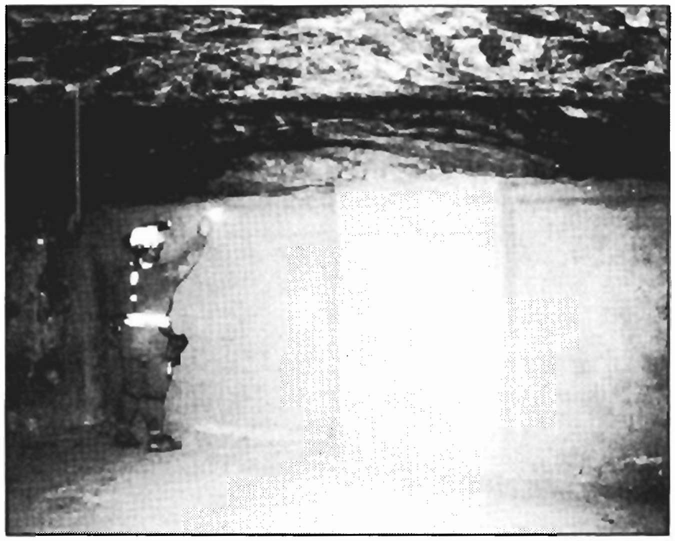


Figure 13.—Condition of the low-density cementitious block seal following a 138-kPa explosion pressure pulse.

Preexplosion air leakage rates through each seal were negligible for pressure differentials up to 0.75 kPa (table 2). Observations of the seals following the 138- to 148-kPa level explosion pressure pulse revealed no outward damage to either design except for very slight hairline cracks in the surface coating (figure 13 and table 5). Subsequent air leakage data showed that each seal maintained acceptable leakage resistance characteristics (see table 2).

Table 5.—Summary of test conditions and results for low-density cementitious block seal designs

Crosscut and seal No.	Seal wall thickness, cm	Pilaster width/ thickness, cm	No. block	Explosion test outcome
1	61	[1]122/122	168	Passed; 148 kPa.
2	61	[2]183/142	192	Passed; 138 kPa.

[1]Coated on both inby and outby face.
[2]Coated only on inby face.

WATER TRAP DESIGNS

PRC's seal research program recently has focused on the capability of various water trap designs in preventing the propagation of flame and gases through the trap during full-scale mine explosions. During these evaluations, a water trap design was judged as a failure if it did not successfully prevent the passage of an explosion flame through the trap and if it did not contain sufficient water within the trap to prevent air passage through the trap following the explosion.

To evaluate these trap designs, a standard solid-concrete-block seal with two 41-cm-wide by 81-cm-thick pilasters was constructed within crosscut No. 1 between B and C drifts of the LLEM. Steel angle, to simulate the keying technique, was used on the ribs and floor on both sides of the seal. All of the block joints were fully mortared and vertically staggered.

Three water trap designs were installed through this seal (figure 14). Two of these three were U-shaped water-pipe trap designs typically used in coal mines. Both were constructed of schedule 40 PVC pipe: one 15 cm in diameter (left side of figure 14), the other 30 cm in diameter (right side of figure 14). Another trap design consisted of a 41-cm-wide by 15-cm-high opening through the center bottom block course of the seal (between the two pilasters at bottom center of figure 14). Three steel I-beams were used to bridge the opening for support of the upper course blocks. On each side of this opening through the seal, a 2-course-high (30-cm) concrete block partition area was constructed. This was designed to create a water pool on each side of the opening with a water level 15 cm higher than that of the top of the opening through the seal. The water pool partition area, on each side of the seal wall, extended 41 cm from the seal wall and was 81 cm long (distance between the pilasters) and 30 cm deep. This trap design is referred to as a water trough. Each of these trap designs was tested separately.

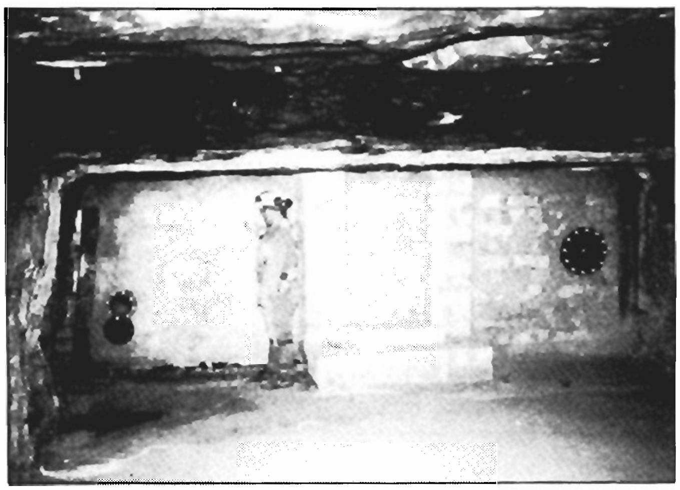


Figure 14.—Three water trap design openings installed through a solid-concrete-block seal.

A worst-case scenario was established for the evaluation of these water trap designs. Many mining operations use a network of drainage pipes connected directly onto the trap on the active side of the seal to remove the water from the area. However, it is also very common in coal mines not to pipe off this water draining through the trap. Therefore, during this study, only the water trap design itself was evaluated without any other drainage devices attached. The CH_4 ignition zone on the C-drift side (representing the sealed area of the mine) of the seal was also extended to encompass the entire first outby crosscut area. This ensured that a flammable CH_4-air atmosphere would be at the trap opening and thus simulate a CH_4 buildup in the sealed area behind the seal. The concentration of the CH_4-air in this larger ignition zone was reduced from 10 pct (which had been used for the 14.3-m-long original zone) to 8.5 pct to maintain the 138-kPa explosion pressure pulse. The water trap was located on the side opposite that of the initial explosion (or on the B-drift side). A 75-m^3 zone of 10 pct CH_4-air surrounded the water trap on this B-drift side (representing the active workings) of the seal. In addition, the traps were evaluated with only that level of water that could be contained within the trap itself, simulating zero-flow conditions. A zero-flow condition would be present for a period following the initial construction of any seal until the water behind the seal reached the trap level. This condition would also be present in sealed areas that produce little or no water. The smaller 15-cm-diam trap held approximately 20 L of water; the larger 30-cm-diam trap held about 190 L of water. Approximately 226 L of water was contained within the water trough system.

The results of the water trap evaluation showed that the three trap designs typically used in coal mines were inadequate when tested under worst-case conditions within the LLEM. The 138-kPa pressure pulse, as generated from the CH_4 ignition on the C-drift side of the seal, removed all of the water from each of the three trap designs (tested separately) and, in several instances, allowed passage of the explosion flame through the trap. During one test using the 15-cm-diam water pipe trap, the explosion pressure pulse pushed the water out of the trap, enabling the explosion flame to then travel through the trap and ignite the CH_4 zone surrounding the trap on the opposite side of the seal, as shown by optical sensor data and video camera. During one test with the water trough and three duplicate tests with the 30-cm-diam water pipe trap designs, sufficient water was dispersed around the trap opening on the B-drift side of the seal to cool and quench any flame that traveled through the trap. This quenching effect resulted in the inability to ignite the surrounding flammable CH_4-air atmosphere. Even though no ignitions occurred, in a worst-case, dry-mine, or zero-flow scenario, the water trap designs could not refill after the explosion and would thus allow the passage of flammable and/or toxic gases from one side of the seal to the other.

These full-scale evaluations revealed two other potential drawbacks associated with these PVC pipe trap designs. First, the PVC trap units must be supported or braced between the bottom of the trap and the mine floor. If the trap was not blocked or braced to the mine floor, the explosion pressure pulse resulted in the separation of the cemented joints and thus the destruction of the trap. In addition to being supported, each of the PVC joint sections must be properly cemented and secured together with screws as well. These screws were No. 12, 2.5-cm-long, self-drilling screws with a rubber sealing washer to minimize water leakages. Explosion tests conducted on the PVC traps without the screws resulted in the separation of the PVC joint sections. With the 15-cm-diam water pipe trap, three screws were equally spaced around each of the joint sections. With the much larger 30-cm-diam water pipe trap, approximately 24 screws were used per joint section. During a test with the 30-cm-diam water pipe trap, the explosion pressure pulse separated the trap from the seal wall at the pipe joint. Although properly cemented, this joint was not secured with screws like the other joints within the trap. The explosion pressure forces acting on the trap exceeded the strength characteristics of the joint cement and resulted in the separation of the trap from the seal wall. Flame passed through this opening in the seal and ignited the flammable CH_4 zone on the other side. In every test scenario where the trap units were both supported and all joints were secured with a combination of cement and screws, the trap units were unaffected by the explosion except for the complete expulsion of the water held within the trap.

Ongoing explosion testing of modified water trap designs are continuing at the LLEM. One such design involved a modification to the water trough design. An additional course of block was installed around the water trough area on the active (B-drift) side of the seal. The installation of this additional course effectively raised the water level approximately 15 cm above the original water trough on the other (C-drift) sealed side of the seal. When subsequently evaluated under explosion conditions, this modified water trough trap design prevented the passage of flame through the trap. Postexplosion observations showed that the water level within the trough on the B-drift side of the seal was to the top of the trough. By simply adding one additional course of block to the active side of the water trough, this modified trap design not only prevented the passage of flame, but also maintained a full water level within the trough, thereby preventing the passage of gases and/or flame through the trap.

Explosion tests were then conducted against a slightly modified 15-cm-diam PVC water pipe trap. The end of the PVC trap was extended vertically on the active side of the seal to enable the water level behind the seal to raise an additional 15 cm (see figure 15). The water level behind the seal was such that the entire 15-cm-diam trap opening through the seal was just below the water level. This had an outcome similar to that obtained by installing an additional course of block to the trough on the active side of the water trough trap design; no explosion flame passed through the 15-cm-diam PVC pipe trap, and the trap maintained a full level of water. This test also showed that as long as the trap opening on the sealed side is lower than the water level, the explosion flame cannot pass through the trap and therefore cannot cause an explosion within the active workings. However, seals are not designed to be water bulkheads; therefore, the water behind the seal must be maintained at the lowest level possible to prevent high head pressures and potential seal failure. For future seal installations, this can be accomplished by lowering the trap opening through the seal to prevent higher water levels behind the seal. Depending on the pipe trap diameter, this may require some digging into the active side mine floor to accommodate the U-shaped pipe trap.

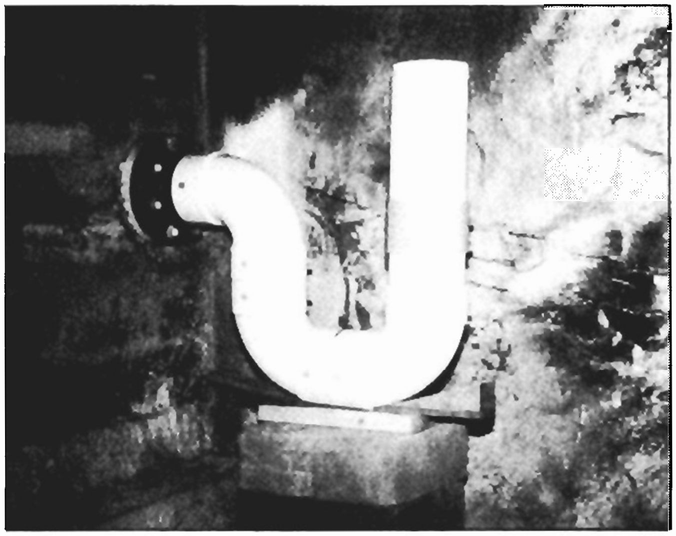


Figure 15.—Typical 15-cm-diam PVC water pipe trap showing the 15-cm-long extension.

These simple modifications to the trap designs allowed the water level in the sealed area to raise to a level just above the trap opening through the seal, resulting in the prevention of the explosion flame from propagating through the trap while, at the same time, maintaining a full water level within the trap. These trap design modifications will provide increased explosion protection to existing water trap installations on seals that are currently producing water. However, these modifications do not address the protection concerns for either new or existing seal installations where there is zero or low water flow conditions. Under these low or zero water flow conditions, the water traps (both existing and modified versions) will be completely emptied of water following the explosion and, in some cases, fail to prevent propagation of the explosion flame through the trap. The focus of our research program is currently on designing and evaluating water trap designs that can prevent explosion flame propagation while maintaining full water levels within the trap following the explosion.

CONCLUSIONS

Four types of construction materials were evaluated in the LLEM as design alternatives to the standard solid-concrete-block design typically used for underground coal mine seals. Each design was evaluated under full-scale mine explosion conditions for its capability to withstand the required pressure pulse of at least 138 kPa while maintaining resistance to air leakage.

Several seal designs were evaluated utilizing two dry-stacked (no mortar) walls consisting of either concrete block or low-density cementitious block with polyurethane foam (with and without added stone aggregate) cores between the walls. The seal designs with the 41-, 46-, and 76-cm-thick polymer foam and aggregate cores sandwiched between two dry-stacked, hollow-core or solid-concrete-block walls survived the 138-kPa pressure pulse while maintaining acceptable air leakage rates, thus meeting the requirements. Four seal designs constructed with 97-cm-thick cores consisting of 91-kg/m^3-density polymer foam (no stone aggregate) did not survive the explosion overpressures. However, a seal constructed with a 51-cm-thick, 203-kg/m^3-density polymer foam core (no stone aggregate) between the two dry-stacked solid-concrete-block walls survived the explosion pressure pulse and subsequent air leakage tests. These tests showed that moisture had caused bonding problems between the polymer and the aggregate and between the polymer and the mine strata. To reduce the adverse effect of moisture on the polymer, dry-bagged aggregate is now used. The seal area must also be properly prepared, which entails removal of all excessive dust, standing water, and moisture accumulations. In addition, it is recommended that a high-density polymer be applied initially to the mine strata to reduce the adverse effects of moisture on the polymer density.

Full-scale explosion testing of cellular concrete seal designs showed that the two-pour construction technique utilized during the injection of the slurry between the 1.2-m-spaced forms did not adversely affect the strength of the seals. Two additional low-density cementitious foam block seal designs constructed with an alternative bonding mortar withstood the required pressure pulse while maintaining acceptable air leakage rates.

Evaluations of several U-shaped water trap pipes and a water trough design typically used in coal mines showed that they did not prevent the passage of the explosion flame and/or gases from one side of a trap to the other following an explosion pressure pulse. Simple modifications, such as an extension pipe on the pipe traps, which can be retrofitted to the various trap designs, have been successfully demonstrated under full-scale explosion conditions to prevent the passage of flame while, at the same time, maintaining an adequate level of water within the trap.

Based on the most recent tests conducted in the LLEM, alternative seal construction materials are now being used regularly in U.S. underground coal mines. PRC's seal research program at Lake Lynn Laboratory will continue to evaluate, under full-scale conditions, innovative seal designs and improved water trap devices. Many of these seal designs will provide increased safety for underground mine workers by reducing materials handling and associated injuries, decreased construction times when installing seals under hazardous fire or potential explosion conditions, and/or enhanced overall seal performance in terms of strength characteristics, air leakage resistance, and better durability in high-convergence areas.

ACKNOWLEDGMENTS

The authors thank Jack M. Teatino, Donald D. Sellers, Frank A. Karnack, and Samuel E. Angelo (miner mechanics), and Paul K. Stefko and Paul D. Kolarosky (mine foremen) of PRC for their research support work required in constructing and evaluating the various seal designs.

REFERENCES

1. U.S. Code of Federal Regulation. Title 30—Mineral Resources; Chapter I—Mine Safety and Health Administration, Department of Labor; Subchapter O—Coal Mine Safety and Health; Part 75—Mandatory Safety Standards— Underground Coal Mines; 1995.

2. Mitchell, D. W. Explosion-Proof Bulkheads - Present Practices. USBM RI 7581, 1971, 16 pp.

3. Greninger, N. B., E. S. Weiss, S. J. Luzik, and C. R. Stephan. Evaluation of Solid-Block and Cementitious Foam Seals. USBM RI 9382, 1991, 13 pp.

4. Stephan, C. R. Omega 384 Block as a Seal Construction Material. MSHA ISD Report No. 10-318-90, Nov. 14, 1990, 15 pp.

5. _____. Construction of Seals in Underground Coal Mines. MSHA ISD Report No. 06-213-90, Aug. 1, 1990, 35 pp.

6. Weiss, E. S., N. B. Greninger, C. R. Stephan, and J. R. Lipscomb. Strength Characteristics and Air-Leakage Determinations for Alternative Mine Seal Designs. USBM RI 9477, 1993, 21 pp.

7. Mattes, R. H., A. Bacho, and L. V. Wade. Lake Lynn Laboratory: Construction, Physical Description, and Capability. USBM IC 8911, 1983, 40 pp.

8. Triebsch, G. F., and M. J. Sapko. Lake Lynn Laboratory: A State-of-the-Art Mining Research Facility. Paper in Proceedings of the Int. Symp. on Unique Underground Structures (Denver, CO, June 12-15, 1990), ch. 75, 1990, pp. 75-1 to 75-21.

9. Sapko, M. J., E. S. Weiss, and R. W. Watson. Size Scaling of Gas Explosions: Bruceton Experimental Mine Versus the Lake Lynn Mine. USBM RI 9136, 1987, 23 pp.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1996—508-103